Determining neutrino oscillation parameters in presence of Non-Standard neutrino Interaction (NSI)

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Reference

- P. B. and Y. Farzan, "CP-Violation and Non-Standard Interactions at the MOMENT," JHEP **1607** (2016) 109 [arXiv:1602.07099 [hep-ph]].
- P. B. and A. N. Khan, "Sensitivities to charged-current nonstandard neutrino interactions at DUNE," arXiv:1607.00065 [hep-ph].

Overview

Introduction

Neutrino Oscillation

There is a mixing between mass and flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \,, \;\; \alpha = e, \mu, \tau, \quad i = 1, 2, 3 \tag{1}$$

PMNS mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \tag{2}$$

Neutrino Oscillation in Vacuum

$$H|\nu_k\rangle = E_k|\nu_k\rangle \tag{3}$$

$$i\frac{d}{dt}|\nu_k(t)\rangle = H|\nu_k(t)\rangle \tag{4}$$

$$|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle \tag{5}$$

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t}|\nu_k\rangle \tag{6}$$

$$|\nu_\alpha(t)\rangle = \sum_\beta \sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k}|\nu_\beta\rangle \tag{7}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j)t} \tag{8}$$

Neutrino Oscillation in Vacuum

$$E_k \simeq E + \frac{m_k^2}{2E} \tag{9}$$

$$E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E} \equiv \frac{m_k^2 - m_j^2}{2E} \tag{10}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* e^{-i \frac{\Delta m_{kj}^2 L}{2E}} \tag{11}$$

Neutrino Oscillation parameters

NuFIT 2.2 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.56$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.348$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.348$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.440^{+0.023}_{-0.019}$	$0.388 \to 0.630$	$0.584^{+0.018}_{-0.022}$	$0.398 \to 0.634$	$0.388 \to 0.632$
$\theta_{23}/^\circ$	$41.5^{+1.3}_{-1.1}$	$38.6 \to 52.5$	$49.9^{+1.1}_{-1.3}$	$39.1 \to 52.8$	$38.6 \to 52.7$
$\sin^2\theta_{13}$	$0.02163^{+0.00074}_{-0.00074}$	$0.01938 \to 0.02388$	$0.02175^{+0.00075}_{-0.00074}$	$0.01950 \to 0.02403$	$0.01938 \to 0.02396$
$\theta_{13}/^\circ$	$8.46^{+0.14}_{-0.15}$	$8.00 \to 8.89$	$8.48^{+0.15}_{-0.15}$	$8.03 \to 8.92$	$8.00 \to 8.90$
$\delta_{CP}/^\circ$	289^{+38}_{-51}	$0 \to 360$	269^{+39}_{-45}	$146 \to 377$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.526^{+0.039}_{-0.037}$	$+2.413 \to +2.645$	$-2.518^{+0.038}_{-0.037}$	$-2.634 \to -2.406$	$\begin{bmatrix}+2.413 \to +2.645 \\ -2.630 \to -2.409\end{bmatrix}$

Neutrino Oscillation in Matter

- Forward elastic scattering processes affect neutrino oscillation

$$H = H_{vac} + H_{mat} \tag{12}$$

$$H_{vac} = U_{PMNS} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^\dagger_{PMNS} \tag{13}$$

$$H_{mat} = \sqrt{2} G_F N_e diag(1, 0, 0) \tag{14}$$

- Assuming neutral-current non-standard neutrino interaction

$$H_{mat} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \tag{15}$$

- NC NSI

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fC}_{\alpha\beta}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f\right) \ , \qquad (19)$$

$\epsilon_{\alpha\beta} = (N_d/N_e)\epsilon^d_{\alpha\beta} + (N_u/N_e)\epsilon^u_{\alpha\beta}$

- CC NSI (pion decay)

$$\mathcal{L}^S = -2\sqrt{2}G_F\sum_\beta(\delta_{\mu\beta} + \varepsilon^{udL}_{\alpha\beta})(\overline{\mu}\gamma_\lambda P_L U_{\beta a}\nu_a)(\bar{d}\gamma^\lambda P_L u)^\dagger \qquad (20)$$

- CC NSI (muon decay)

$$\mathcal{L}^L = -2\sqrt{2}G_F\sum_{\alpha,\beta}(\delta_{\alpha\beta} + \varepsilon^{L}_{\alpha\beta})(\overline{e}\gamma_\lambda P_L U_{\alpha a}\nu_a)(\overline{\mu}\gamma^\lambda P_L U_{\beta b}\nu_b)^\dagger \qquad (21)$$

- Current constraints on NC NSI parameters (arXiv:1307.3092)

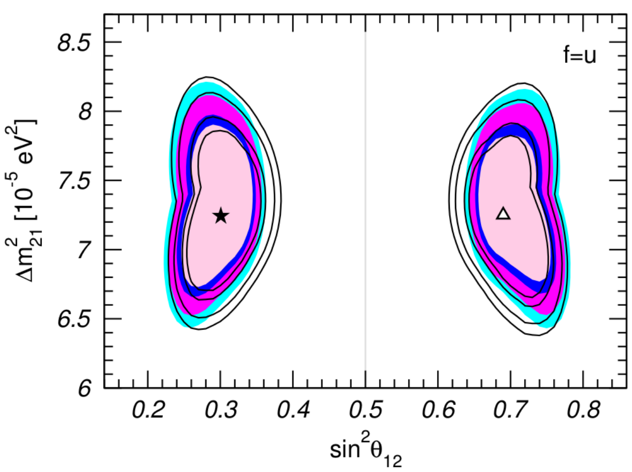
$$\begin{aligned} |\epsilon_{e\mu}| &< 0.16 \\ |\epsilon_{e\tau}| &< 0.26 \\ |\epsilon_{\mu\tau}| &< 0.02 \end{aligned} \tag{22}$$

and

$$\begin{array}{ccccc} -0.018 & < & \epsilon_{\tau\tau} - \epsilon_{\mu\mu} & < & 0.054 \\ 0.35 & < & \epsilon_{ee} - \epsilon_{\mu\mu} & < & 0.93. \end{array} \tag{23}$$

- NC NSI affect neutrino osillation during propagation in matter
- $a_{CC} = 2\sqrt{2} G_F N_e E$
- CC NSI affect flavour change in neutrino production and detection

LMA-Dark



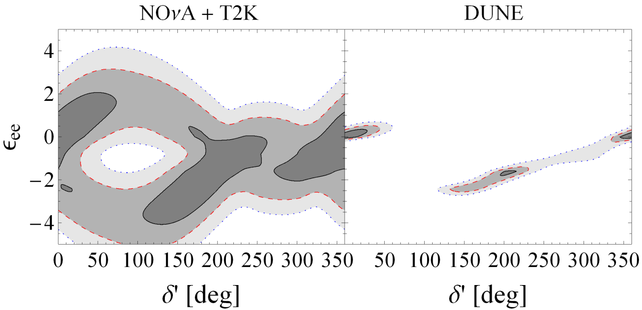
M. C. Gonzalez-Garcia and M. Maltoni, JHEP **1309** (2013) 152, arXiv:1307.3092

Current Constraints on CC NSI

parameter	Current constraints (90%C.L.)
$\lvert\epsilon^{s}_{\mu e}\rvert$	0.026
$\lvert\epsilon^{s}_{\mu\mu}\rvert$	0.078
$\lvert\epsilon^{s}_{\mu\tau}\rvert$	0.013
$\lvert\epsilon^{d}_{ee}\rvert$	0.041
$\lvert\epsilon^{d}_{e\mu}\rvert$	0.026
$\lvert\epsilon^{d}_{\mu e}\rvert$	0.025
$\lvert\epsilon^{d}_{\mu\mu}\rvert$	0.078
$\lvert\epsilon^{d}_{\tau e}\rvert$	0.041
$\lvert\epsilon^{d}_{\tau\mu}\rvert$	0.013

C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP **0908** (2009) 090 [arXiv:0907.0097 [hep-ph]].

Degeneracy between NSI and δ_{CP}



A. de Gouva and K. J. Kelly, Nucl. Phys. B **908** (2016) 318 [arXiv:1511.05562 [hep-ph]].

- Muon disapperance probability in presence of NC NSI

$$
\begin{aligned}
P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
- |\epsilon_{\mu\tau}| \cos\phi_{\mu\tau} \sin 2\theta_{23} \left[\sin^2 2\theta_{23} \frac{a_{\rm CC} L}{2E} \sin \frac{\Delta m_{31}^2 L}{2E} \right. \\
\left. + 4 \cos^2 2\theta_{23} \frac{a_{\rm CC}}{\Delta m_{31}^2} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \right] \\
+ \frac{1}{2} (|\epsilon_{\mu\mu}| - |\epsilon_{\tau\tau}|) \sin^2 2\theta_{23} \cos 2\theta_{23} \left[\frac{a_{\rm CC} L}{2E} \sin \frac{\Delta m_{31}^2 L}{2E} \right. \\
\left. - 4 \frac{a_{\rm CC}}{\Delta m_{31}^2} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \right]
\end{aligned}
\tag{24}
$$

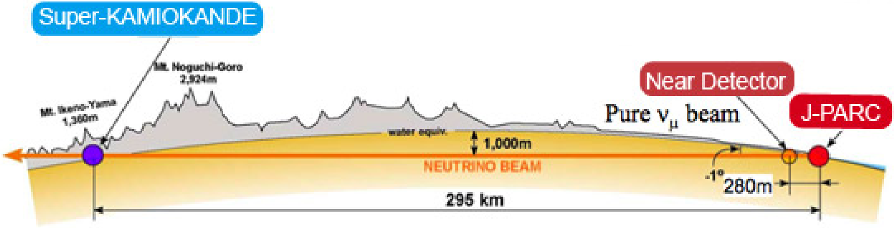
$$
\begin{aligned}
P^{\rm mat}_{\nu^s_\mu\to\nu^d_e} &= 4\tilde{s}_{13}\sin^2\theta_{23}\left(\tilde{s}_{13} + 2\left(|\epsilon_{e\mu}|\cos(\phi_{e\mu}+\delta_{\rm CP}) + |\epsilon_{e\tau}|\cos(\phi_{e\tau}+\delta_{\rm CP})\right)\sin\theta_{23}\frac{a_{\rm CC}}{\Delta m^2_{31}-a_{\rm CC}}\right) \\
&\sin^2\frac{(\Delta m^2_{31}-a_{\rm CC})L}{4E} + \left(\frac{\Delta m^2_{21}}{a_{\rm CC}}\right)^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\frac{a_{\rm CC}L}{4E} \\
&+ 4(|\epsilon_{e\mu}|\cos\phi_{e\mu} - |\epsilon_{e\tau}|\cos\phi_{e\tau})\frac{\Delta m^2_{21}}{a_{\rm CC}}\sin 2\theta_{12}\cos^3\theta_{23}\sin^2\frac{a_{\rm CC}L}{4E} \\
&+ \Bigg(-\frac{\Delta m^2_{21}}{a_{\rm CC}}\tilde{s}_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\delta_{\rm CP} - 4|\epsilon_{e\mu}|\tilde{s}_{13}\sin\theta_{23}\cos^2\theta_{23}\cos(\phi_{e\mu}+\delta_{\rm CP}) \\
&+ 4|\epsilon_{e\tau}|\tilde{s}_{13}\sin^2\theta_{23}\cos\theta_{23}\cos(\phi_{e\tau}+\delta_{\rm CP}) - 2|\epsilon_{e\mu}|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}\sin^2\theta_{23}\cos\theta_{23}\cos\phi_{e\mu} \\
&\frac{\Delta m^2_{31}}{\Delta m^2_{31}-a_{\rm CC}} - 2|\epsilon_{e\tau}|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}\sin\theta_{23}\cos^2\theta_{23}\cos\phi_{e\tau}\frac{\Delta m^2_{31}}{\Delta m^2_{31}-a_{\rm CC}}\Bigg)\Bigg[\sin^2\frac{a_{\rm CC}L}{4E} \\
&-\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\frac{(\Delta m^2_{31}-a_{\rm CC})L}{4E}\Bigg] + \Bigg(-\frac{1}{2}\frac{\Delta m^2_{21}}{a_{\rm CC}}\tilde{s}_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta_{\rm CP} \\
&-2|\epsilon_{e\mu}|\tilde{s}_{13}\sin\theta_{23}\cos^2\theta_{23}\sin(\phi_{e\mu}+\delta_{\rm CP}) + 2|\epsilon_{e\tau}|\tilde{s}_{13}\sin^2\theta_{23}\cos\theta_{23}\sin(\phi_{e\tau}+\delta_{\rm CP}) \\
&+|\epsilon_{e\mu}|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}\sin^2\theta_{23}\cos\theta_{23}\sin\phi_{e\mu}\frac{\Delta m^2_{31}}{\Delta m^2_{31}-a_{\rm CC}} + |\epsilon_{e\tau}|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}\sin\theta_{23} \\
&\cos^2\theta_{23}\sin\phi_{e\tau}\frac{\Delta m^2_{31}}{\Delta m^2_{31}-a_{\rm CC}}\Bigg)\Bigg[\sin\frac{a_{\rm CC}L}{2E} - \sin\frac{\Delta m^2_{31}L}{2E} + \sin\frac{(\Delta m^2_{31}-a_{\rm CC})L}{2E}\Bigg]
\end{aligned}
\tag{25}
$$

- If a_{CC} is negligible

$$P_{\nu_\mu \to \nu_e} = 4 \sin^2 \theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} + \frac{\Delta m_{21}^2 L}{4E} \sin \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} (\cos \delta_{\rm CP} \sin \frac{\Delta m_{31}^2 L}{2E} - 2 \sin \delta_{\rm CP} \sin^2 \frac{\Delta m_{31}^2 L}{4E}). \tag{26}$$

T2K, NOνA, MOMENT, DUNE

T2K

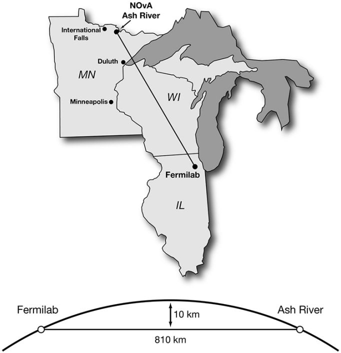


http://www2.warwick.ac.uk/fac/sci/physics/research/epp/exp/t2k/

T2K

- 2 years in neutrino and 6 years in anti-neutrino mode
- fiducial mass of SK: 22.5 kton
- Energy resolution is 85 MeV
- $400MeV < E < 1.2GeV$
- 2.5% normalization uncertainty for disappearance, 5% appearanec
- free normalization for quasi-elastic events
- Background: lepton flavor misidentification, neutral-current events, charge misidentification and intrinsic background
- Background normalization uncertainty is 20%
- 5% uncertainties of matter density profile, (PREM)
- We used GLoBES for simulation

NOνA

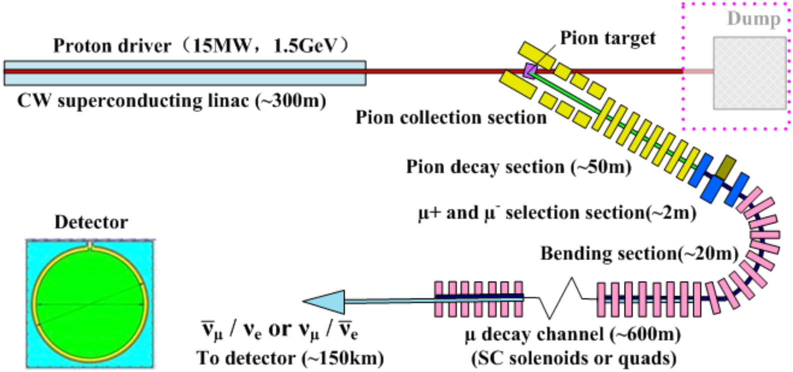


http://www.universetoday.com/109444/nova-experiment-nabs-its-first-neutrinos/

NOνA

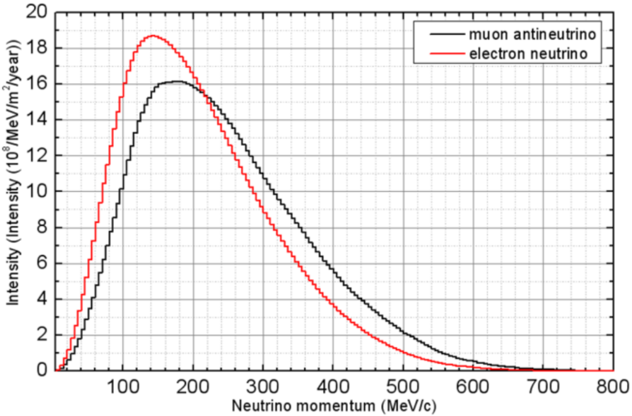
- 3 years in each mode
- 25 kton fiducial mass
- $1GeV < E < 3.5GeV$
- energy resolution is $10\%\sqrt{E}$ for electron neutrino and $5\%\sqrt{E}$ for muon neutrino
- normalization uncertainty is 5%
- Background: neutral current interaction, lepton flavor misidentification and intrinsic background

MOMENT



https://indico.cern.ch/event/351600/contributions/1754021/

MOMENT



https://indico.cern.ch/event/351600/contributions/1754021/

- MuOn decay MEdium baseline NeuTrino beam facility

MOMENT

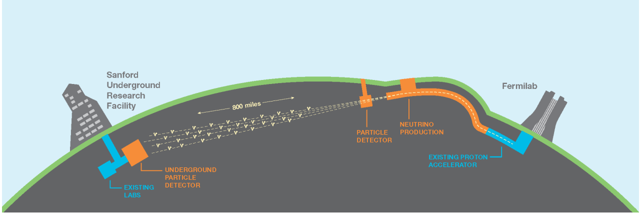
- baseline is 150 km
- 500 kton Gd-doped water Cherenkov detector
- muon mode, $\mu^- \to e^- \bar{\nu}_e \nu_\mu$; and anti-muon mode, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
- $50 MeV < E < 700 MeV$ with peak around 150 MeV
- dominant interaction modes are quasi-elastic interactions:

$$\nu_e + n \to p + e^- \qquad \bar{\nu}_\mu + p \to n + \mu^+$$

$$\bar{\nu}_e + p \to n + e^+ \qquad \nu_\mu + n \to p + \mu^-$$

- Charge Identification is 80 %
- background: charge misidentification, atmospheric neutrinos, flavor misidentification
- neutrino flux of each flavor mode at the detector equal to 4.7×10^{11} m^{-2} year^{-1}
- 5 years of data taking in each mode

DUNE



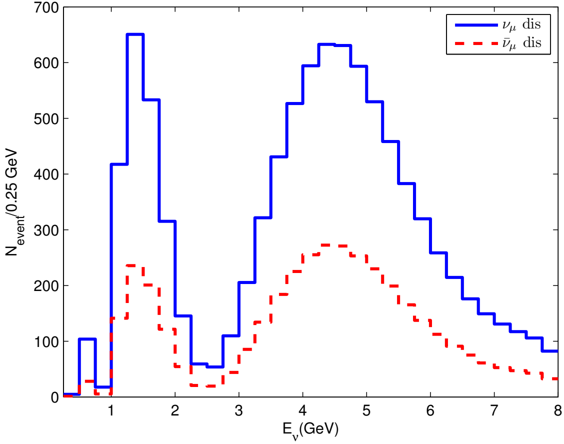
http://lbnf.fnal.gov/

- Deep Underground Neutrino Experiment (DUNE)
- 1300 km baseline
- $250MeV < E < 8GeV$ peak around 3 GeV
- 3 years of data taking in each mode

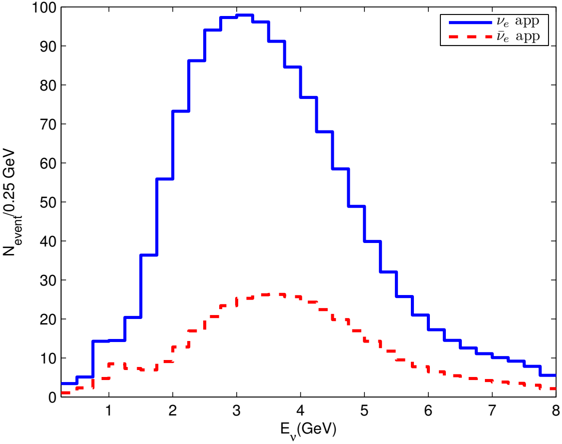
DUNE

- Liquid Argon Time-Projection Chamber(LArTPC) with 34 kton fiducial mass
- near detector: 5 ton at 460 m
- NC events, lepton flavor misidentification and intrinsic background
- $15\%/\sqrt{E(GeV)}$ and $20\%/\sqrt{E(GeV)}$ energy resolution for CC detection of electron neutrino and muon neutrino
- flux uncertainty is 5% and flux uncertainty of background is 10%

Number of events by FD



Number of events by FD

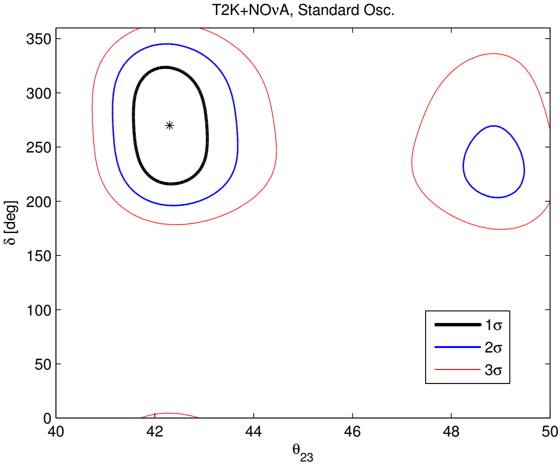


Results

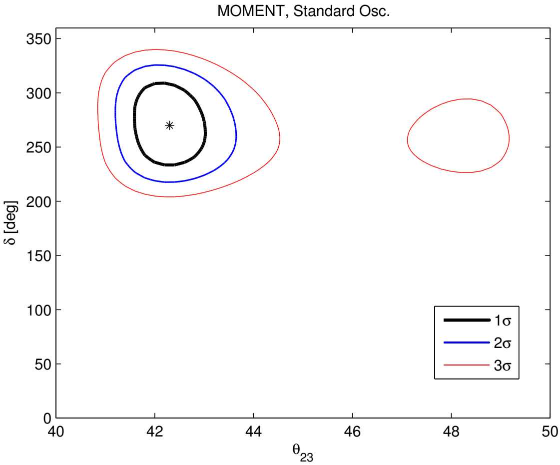
Details of our analysis

- at lower energies matter effect has less impact on neutrino oscillation ($a_{CC} = 2\sqrt{2}G_F N_e E$)
- Effect of NC NSI on determination of θ_{23} octant and δ_{CP}, for T2K, NOνA and MOMENT
- Constraining NC NSI by T2K, NOνA and MOMENT
- Effect of CC NSI on determining θ_{23} octant and δ_{CP} by DUNE
- Constraints on CC NSI by near and far detectors of DUNE

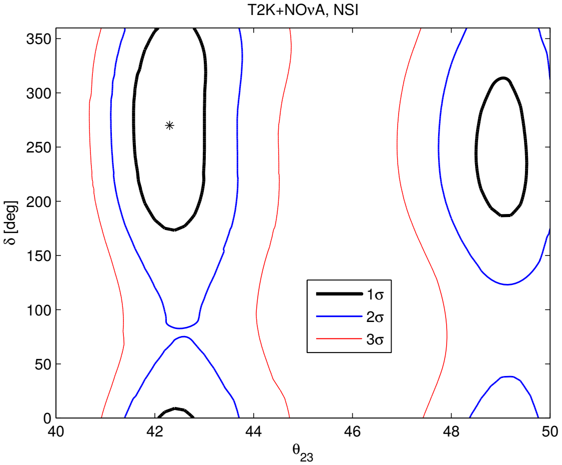
Determination of θ_{23} octant and δ_{CP}



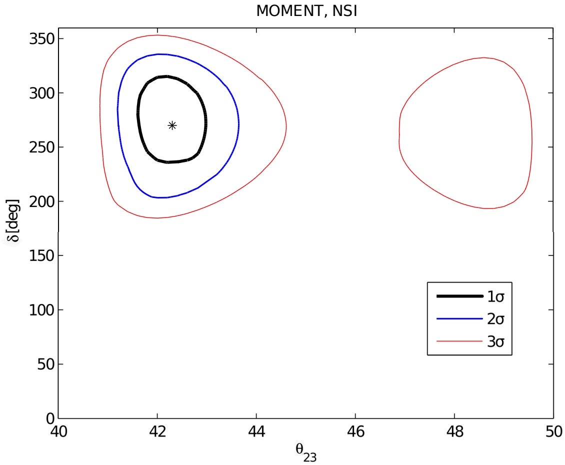
Determination of θ_{23} octant and δ_{CP}



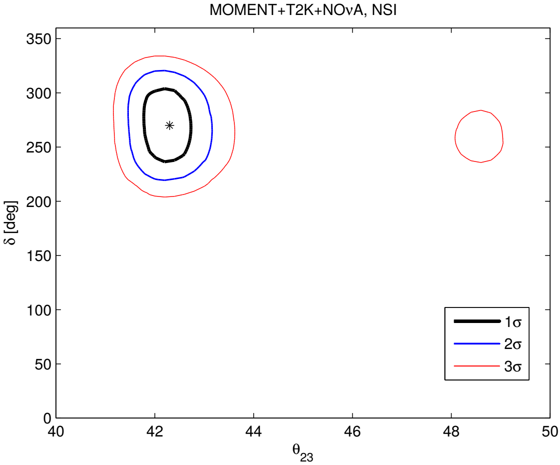
Determination of θ_{23} octant and δ_{CP}



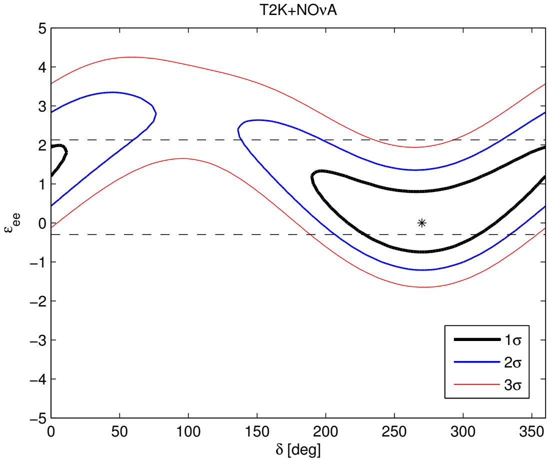
Determination of θ_{23} octant and δ_{CP}



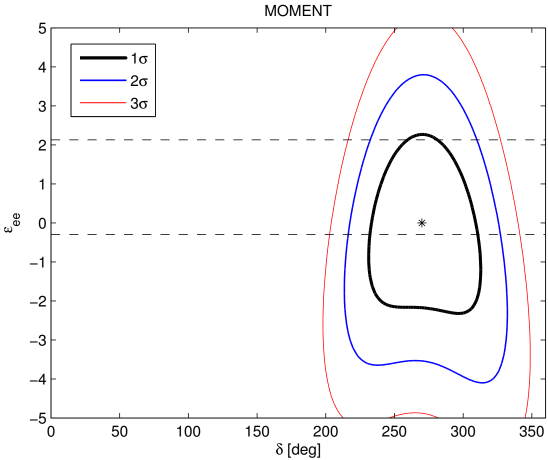
Determination of θ_{23} octant and δ_{CP}



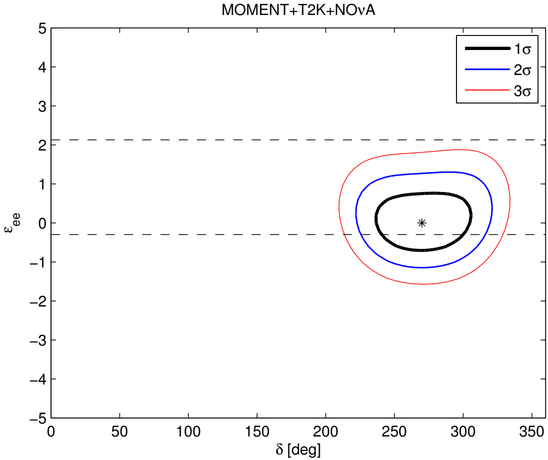
Sensitivity to ϵ_{ee} and δ_{CP}



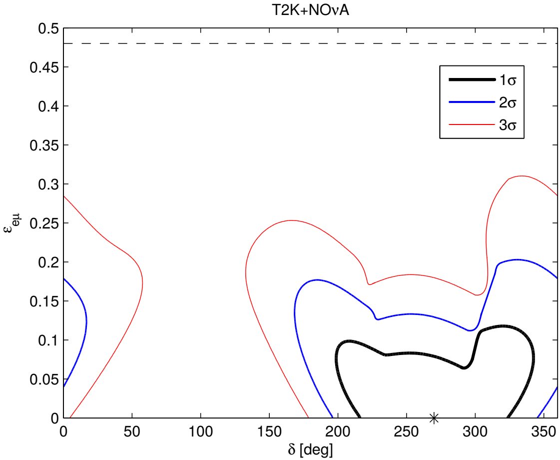
Sensitivity to ϵ_{ee} and δ_{CP}



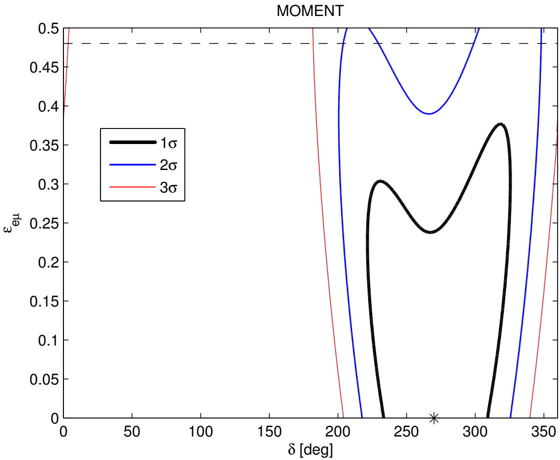
Sensitivity to ϵ_{ee} and δ_{CP}



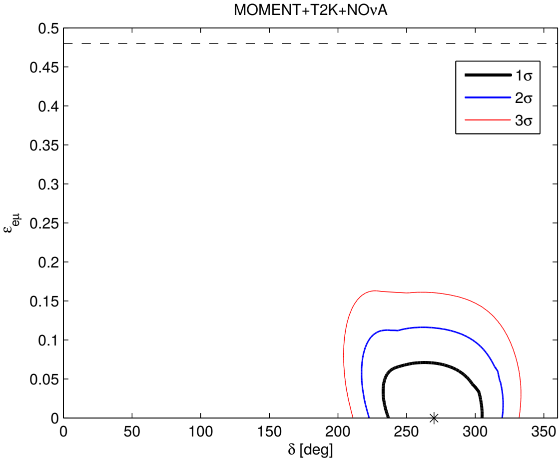
Sensitivity to $\epsilon_{e\mu}$ and δ_{CP}



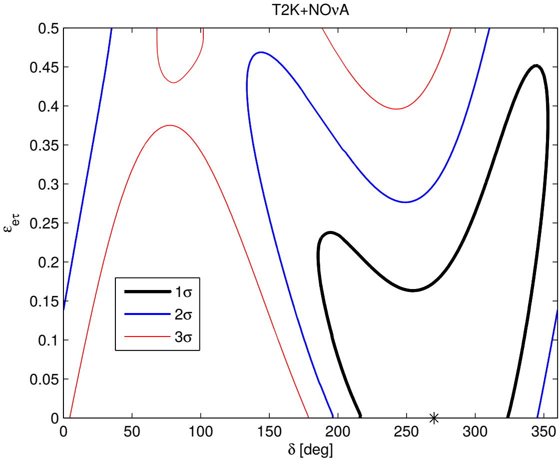
Sensitivity to $\epsilon_{e\mu}$ and δ_{CP}



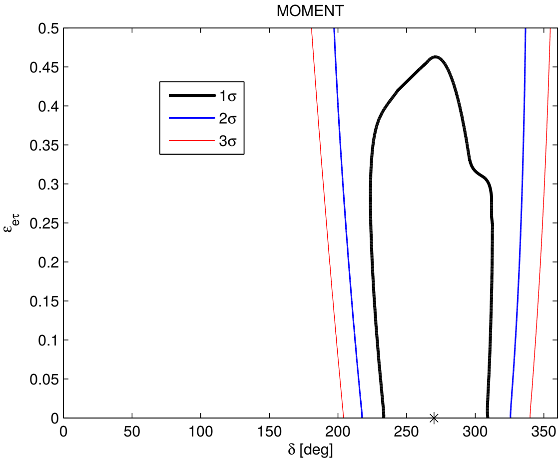
Sensitivity to $\epsilon_{e\mu}$ and δ_{CP}



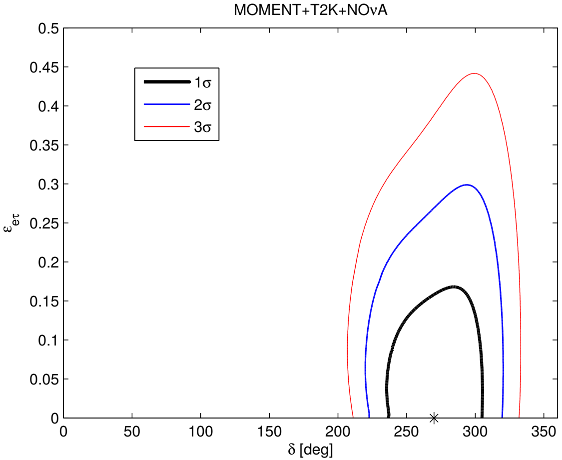
Sensitivity to $\epsilon_{e\tau}$ and δ_{CP}



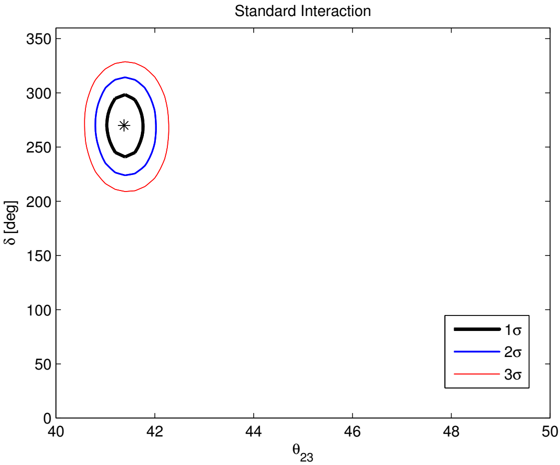
Sensitivity to $\epsilon_{e\tau}$ and δ_{CP}



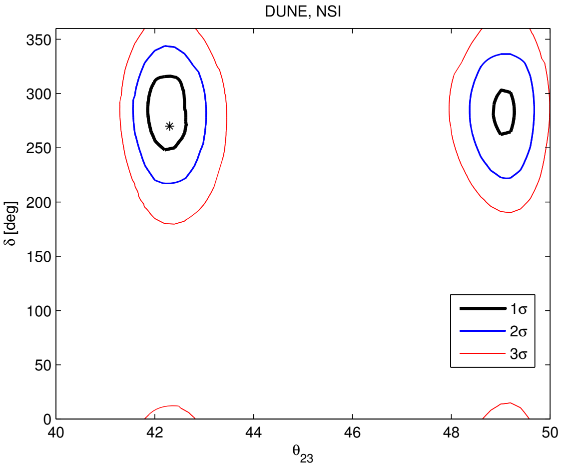
Sensitivity to $\epsilon_{e\tau}$ and δ_{CP}



Determination of θ_{23} octant and δ_{CP} by DUNE

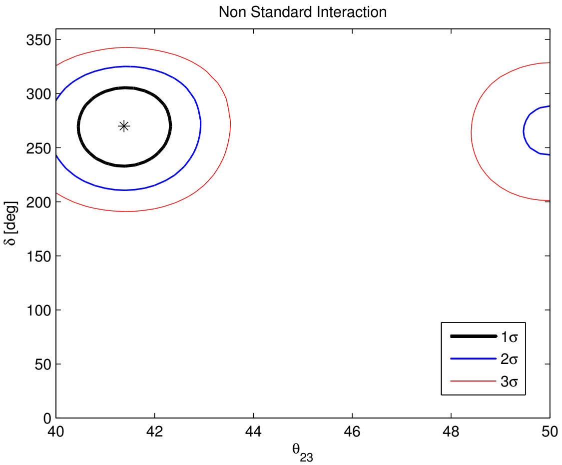


Determination of θ_{23} octant and δ_{CP} by DUNE



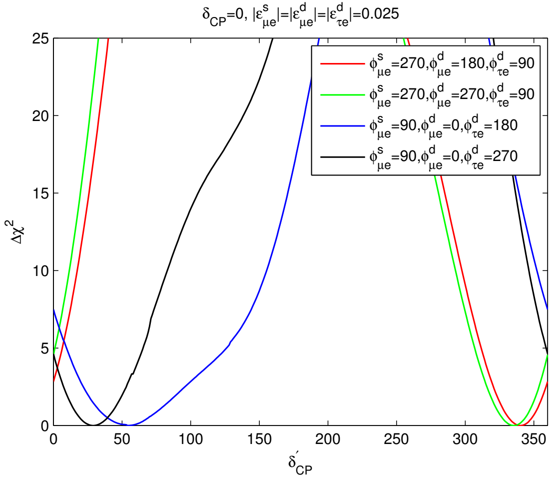
NC NSI

Determination of θ_{23} octant and δ_{CP} by DUNE



CC NSI

Inducing fake CP phase by CC NSI



Constraints on CC NSI by near and far detectors of DUNE

parameter	Far Detector	Near detector	Current constraints
$\|\epsilon^s_{\mu e}\|$	0.016	0.013	0.026
$\|\epsilon^s_{\mu\mu}\|$	0.028	0.007	0.078
$\|\epsilon^s_{\mu\tau}\|$	0.074	-	0.013
$\|\epsilon^d_{ee}\|$	0.057	0.005	0.041
$\|\epsilon^d_{e\mu}\|$	0.049	-	0.026
$\|\epsilon^d_{\mu e}\|$	0.019	0.013	0.025
$\|\epsilon^d_{\mu\mu}\|$	0.032	0.007	0.078
$\|\epsilon^d_{\tau e}\|$	0.113	-	0.041
$\|\epsilon^d_{\tau\mu}\|$	0.076	-	0.013

C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP **0908** (2009) 090 [arXiv:0907.0097 [hep-ph]].

Summary

Summary

- measurement of oscillation parameters can be affected by NSI
- Effect of NC NSI can be studied by combining a low energy and a high energy neutrino experiment
- CC NSI can induce large amount of fake CP phase in DUNE
- Near detector of DUNE is important to constrain CC NSI

Thank you for your attention.